White dwarfs and Galactic dark matter

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ABSTRACT

We discuss the recent discovery by Oppenheimer et al (2001) of old, cool white dwarf stars, which may be the first direct detection of Galactic halo dark matter. We argue here that the contribution of more mundane white dwarfs of the stellar halo and thick disk would contribute sufficiently to explain the new high velocity white dwarfs without invoking putative white dwarfs of the dark halo. This by no means rules out that the dark matter has been found, but it does constrain the overall contribution by white dwarfs brighter than $M_V \approx 16$ to significantly less than 1% of the Galactic dark matter. This work confirms a similar study by Reylé et al (2001).

Key words: Galaxy – dark matter; Galaxy – structure

1 GALACTIC DARK MATTER AS FAINT STARS?

The MACHO and EROS microlensing projects have detected a microlensing signal from dark objects in the Galactic halo (Alcock et al. (2000) (The MACHO collaboration), and Lassarre et al (2000) (The EROS Collaboration). Taken together, their results show the microlensing can be explained by a Galactic dark halo 20% of which is in the form of approximately 0.5 $M_\odot$ objects. This suggests that the responsible objects could be low mass main sequence red dwarf stars, or white dwarf stars, but in order to have escaped detection to date, they must be very faint.

Red dwarfs are too luminous, or they would have been detected directly in the Hubble Deep Field (HDF) (Flynn et al 1996, Elson et al 1996 and Mendez et al 1996). White dwarfs were considered more difficult to rule out directly, until the surprising discovery was made that white dwarfs which have had long enough to cool, cease becoming fainter and redder, but remain at approximately constant luminosity while becomeing *bluer*, due to the development of H_2 in their atmospheres which induce very non-blackbody spectra (Hansen, 1999a, 1999b).

The possibility that very faint, blue objects had been found arose when the HDF was imaged at a second epoch and analysed by Ibata et al (2000). The number of moving objects, their colours, magnitudes and proper motions were all consistent with the detection of a significant fraction of the dark halo matter in the form of old, cool white dwarfs. However, a third epoch observation of the HDF did not confirm the proper motions of the objects (Richer, 2001), but the idea that the dark matter had been detected had already spurred many groups to search for local counterparts — with some degree of success. As a result, a number of very low lu-

minosity white dwarfs have turned up in new proper motion studies by Ibata et al (2000), Hodgkin et al (2000), Scholz et al (2000), Goldman (2000), de Jong et al (2000) and Oppenheimer et al (2001), along with a very low luminosity white dwarf identified by Ruiz et al (1995), now viewed with new significance. A colour magnitude diagram for these objects in shown in Figure 1. The recently discovered white dwarfs are shown as triangles — they are all fainter than the end of the white dwarf cooling sequence at $M_R \approx 15.5$, and have velocities typical of the spheroid white dwarfs.

Oppenheimer et al (2001 — hereafter OHDHS) have conducted the largest of these recent surveys. They discovered 38 high velocity white dwarfs and derived a space density for their objects which corresponds to approximately 2% of the Galactic dark halo density at the Sun (aproximately 0.01 $M_\odot$ pc^{-3}). This is a small but significant fraction of the dark halo density, not high enough to explain the microlensing events (which require that about 20% of the dark halo be in the form of ≈ 0.5 $M_\odot$ objects, but still significantly higher than the expected contribution of white dwarfs from all the well understood Galactic stellar populations — disk, thick disk, and stellar halo (or spheroid).

A very similar survey to OHDHS, in terms of the local volume of space surveyed for high proper motion stars, is the Luyten Half Second catalog, Luyten (1979). Flynn et al (2001) have searched the LHS and two other older proper motion surveys for nearby dark halo white dwarf candidates. The LHS covers more than half the sky, has a limiting magnitude of $V = 18.4$, with proper motions in the range 0.2 to 0.5 arcsec/year. A recent independent analysis (Monet et al 2000) shows that the LHS is substantially (90%) complete within these limits, based on a new, deeper survey over a small area within the LHS.
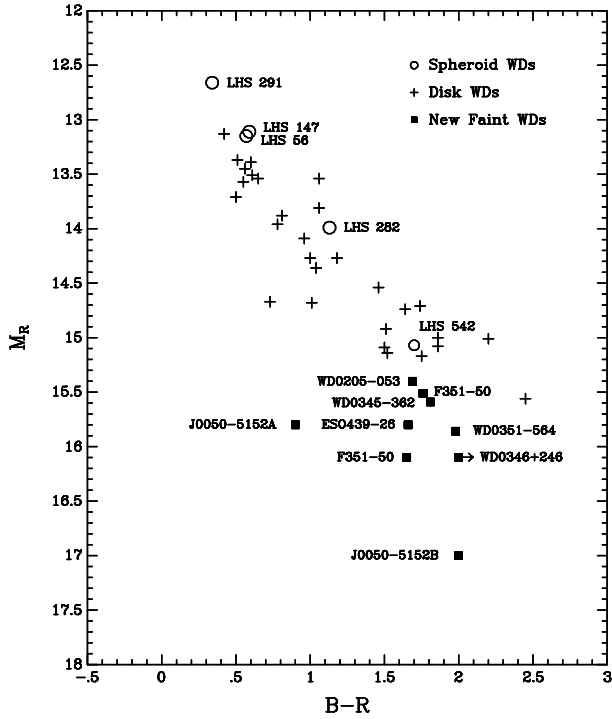
Figure 1. Colour $(B - R)$ versus absolute magnitude (in the R-band) diagram of nearby white dwarfs. Disk white dwarfs are shown by crosses, and spheroid white dwarfs as circles. Until recently, the faintest white dwarfs known were at $M_R \approx 16$, but recently four white dwarfs have turned up in new surveys designed to probe for them (squares). These objects are shown as triangles. One object, J0050-5152, is a binary, the secondary being much fainter and its status as a white dwarf is still to be confirmed. All of these new white dwarfs are still relatively bright, and probably not faint enough to be good dark matter candidates.

Gibson and Flynn (2001) have searched the LHS for objects of the type detected by OHDHS, but found at most a few, even though the survey covers a similar volume. If 2% of the local dark matter is composed of white dwarfs, then a few tens of objects had been expected in the LHS, whereas Flynn et al (2001) had earlier analysed the LHS and two other proper motion surveys in detail, and had found no convincing evidence that any of the high proper motion objects could be associated with "dark halo white dwarfs". All the objects were broadly consistent with coming from the visible Galactic populations.

An alternative explanation for the OHDHS white dwarfs is that they are from existing Galactic populations, and do not represent a new population from the dark halo. That they are members of the thick disk has been argued by Reid et al (2001) and Hansen (2001). We also argue for this view in this paper by modelling the expected numbers of white dwarfs which would be found in proper motion surveys from the known Galactic populations. Our work supports a similar, independent study by Reylé et al (2001).

Table 1. Adopted Luminosity function for disk M dwarfs

M_V	$\log \Phi(M_V)$ stars pc$^{-3}M_V^{-1}$	M_V	$\log \Phi(M_V)$ stars pc$^{-3}M_V^{-1}$
10	−2.12	14	−2.30
11	−1.92	15.5	−2.67
12	−1.89	17.5	−2.61
13	−2.19		

Table 2. Adopted Luminosity function for disk white dwarfs

M_V	$\log \Phi(M_V)$ stars pc$^{-3}M_V^{-1}$	M_V	$\log \Phi(M_V)$ stars pc$^{-3}M_V^{-1}$
11.0	−4.02	14.0	−2.93
11.5	−3.92	14.5	−3.03
12.0	−3.82	15.0	−2.98
12.5	−3.54	15.5	−3.09
13.0	−3.22	16.0	−4.14
13.5	−3.06	16.5	−4.50

2   MODEL OF LOW LUMINOSITY STARS IN THE SOLAR NEIGHBOURHOOD

We have built a model of the low mass stellar content of the Solar neighbourhood, including the luminosity function, density and kinematics, in order to simulate actual proper motion surveys via a Monte-Carlo technique. The model allows us to predict the expected number of low mass stars which would be recovered in a proper motion survey directed toward any point on the sky, covering a given area, with a given apparent magnitude limit and a detection window of proper motions. For example, the LHS catalog covers a little more than half the sky centered on the Northern hemisphere, has an apparent magnitude limit of $R = 18.6$, and recovered proper motions μ in the window $0.5 < \mu < 2.5$ arcseconds per year.

We model a sphere centered on the Sun with a radius of up to 288 pc, which is sufficiently distant from the Sun for all the surveys we consider. Only low luminosity ($M_V > 12.5$) stars are included in the model.

2.1   Populations in the Model

The local Galactic components represented in the model are the disk, the thick disk, the stellar halo and the dark halo.

• *The disk* component consists of M dwarfs and white dwarfs. The M dwarfs are drawn from a luminosity function shown in Table 1, which has been measured from faint star counts with HST (Zheng et al 2001). The white dwarfs are drawn from the luminosity function shown in Table 2, which comes from Liebert et al (1988).

The disk white dwarfs have velocity dispersion components $\sigma = (\sigma_U, \sigma_V, \sigma_W)$ (where U, V, W are the usual space velocities in the directions of the Galactic center, Galactic rotation and perpendicular to the Galactic plane) of $\sigma = (40, 30, 20)$ km s^{-1}, and a mean motion (asymmetric drift) relative to the Sun of -20 km s^{-1}. For the disk M dwarfs, we adopt velocity dispersion components of $\sigma = (35, 25, 15)$

km s^{-1}, and a asymetric drift, $V_{\text{ass}} = 15$ km s^{-1}. These values are slightly lower than for the white dwarfs, because the mean age of the M dwarfs is certainly lower than the white dwarfs. The young M dwarf component is measured to have $\sigma = (30, 17, 12)$ km s^{-1}, and the old M dwarf component $\sigma = (56, 34, 31)$ km s^{-1}, in an analysis of the Hipparcos results by Upgren et al (1997). In both the surveys analysed in this paper, the number of M dwarfs recovered from the proper motion windows is quite sensitive to the kinematics adopted; our values have been choosen to produce about the right number of M dwarfs. Note though thata our main interest is to predict the number of white dwarfs in the proper motion surveys, while the M dwarfs are only included as a consistency check on the modelling. The number of white dwarfs predicted in the surveys is less sensitive to the adopted kinematics, because the white dwarfs are generally closer than the M dwarfs.

• *The thick disk* component of the model consists of white dwarfs selected from the same luminosity function as the disk white dwarfs, but with space density of 5% of the disk (Reylé and Robin, 2001). This is consistent with recent estimates of the thick disk density as between 2% and 10% of the disk density (Kerber et al 2001). We adopt an uncertainty in the thick disk local normalisation of about a factor of two. The thick disk stars are given velocity dispersion components $\sigma = (80, 60, 40)$ km s^{-1}, and an asymetric drift $V_{\text{ass}} = 40$ km s^{-1}(see e.g. Morrison et al 1990). We also include thick disk M dwarfs, selected from the same luminosity function as the disk M dwarfs, with a normalisation of 5% of the disk, and with the same kinematic parameters as the thick disk white dwarfs.

The significantly larger space motions of the thick disk stars means that they are several times more likely to be found in a typical proper motion survey than disk stars. Reylé et al (2001) model the thick disk in their study of white dwarf proper motions as $\sigma = (67, 51, 42)$ km s^{-1}and $V_{\text{ass}} = 53$ km s^{-1}. We have found that adopting either ours or Reylé et al's kinematics for the thick disk ends up giving quite similar results, i.e. the model predictions are not very sensitive to the adopted thick disk kinematics.

• *The stellar halo*, (or spheroid) part of the model consists of white dwarfs drawn from a luminosity function due to Liebert (2001, private communication). The luminosity function is based on 7 white dwarfs, identified as members of the "halo" on the basis of a high tangential velocity, $V_{\text{tan}} > 160$ km s^{-1}obtained as part of an ongoing analysis of all the faint stars in the LHS. The luminosity function is shown in Table 3. Note that we have converted bolometric magnitudes to V-band magnitudes using Eqn 1 of Liebert et al (1988). The total number density in these objects is 3.2×10^{-5} stars pc^{-3} which corresponds to a mass density of 1.9×10^{-5} M$_\odot$ pc^{-3} for a white dwarf mass of 0.6 M$_\odot$. This is approximately 15% of the local mass density of the stellar halo (as seen in subdwarfs) of 1.5×10^{-4} M$_\odot$ pc^{-3} (Fuchs and Jahreiß, 1997).

For the stellar halo we adopt velocity dispersion components of $\sigma = (141, 106, 94)$ km s^{-1}(Chiba and Beers, 2001) and an asymetric drift of 180 km s^{-1}(i.e. there is a small net rotation in the Galactocentric coordinate frame). The adopted values have very little impact on the conclusions of the paper, because stars with such high velocities populate the proper motion selection window quite well. For exam-

Table 3. Adopted Luminosity function for stellar halo white dwarfs

M_{bol}	M_V	$\log \Phi(M_V)$ stars pc^{-3}M_V^{-1}
11.75	12.10	−6.15
14.85	15.25	−4.50

Table 4. Kinematic parameters of populations in the model

Population	$(\sigma_U, \sigma_V, \sigma_W)$ km s^{-1}	V_{as} km s^{-1}
Disk M dwarfs	$(35, 25, 15)$	15
Disk white dwarfs	$(40, 30, 20)$	20
Thick disk	$(80, 60, 40)$	40
Stellar halo	$(141, 106, 94)$	180
Dark halo	$(156, 156, 156)$	220

ple, changing these values to $\sigma = (131, 106, 85)$ km s^{-1}and an asymetric drift of 229 km s^{-1}(as used by Reylé et al 2001) only changes the predicted number of white dwarfs by a few percent.

We further include stellar halo M dwarfs, drawn from the disk M dwarf luminosity function, but with a local density reduced by a factor of 500 (see e.g. Morrison 1993). They are assigned the same kinematics as the white dwarf stellar halo.

• *The dark halo* part of the model consists of white dwarfs only. We adopt velocity dispersion components of $\sigma = (156, 156, 156)$ km s^{-1} and an asymetric drift of $V_{\text{as}} = 220$ km s^{-1}, which simulates an isothermal population with a density falloff with Galactic radius of $\rho \propto R^{-2}$, i.e. a sufficient but not necessary condition to explain the flat Galactic rotation curve. Our starting point for the mass density of these stars is 2% of the local dark halo density of 0.008 M$_\odot$ pc^{-3} (Gates et al 1998) with an average WD mass of 0.6 M$_\odot$, as adopted in the OHDHS survey.

We have adopted a very simple luminosity functions for the dark halo white dwarfs. We give all the dark halo white dwarfs the same absolute magnitude, $M_V = 15.9$, which is the faintest absolute magnitude of any of the putative dark halo white dwarfs found in the OHDHS survey. We show that this choice, combined with a 2% dark halo, leads to significantly larger numbers of dark halo white dwarfs in both surveys than actually observed. Any other choice of luminosity function which is still consistent with the WDs in the OHDHS sample (i.e. all stars are brighter than $M_V = 15.9$) would produce an even greater disagreement between the simulations and the LHS and the number of recovered WDs in the OHDHS sample.

The *dark halo white dwarfs* share similar kinematic properties with the *stellar halo white dwarfs* (i.e. high random velocities), but differ from them in a key respect worth pointing out (although it has no effect on the modelling or conclusion in this paper). The density distribution of the *stellar halo* is well determined by luminous stars, and follows a power law outward from the Galactic center, $\rho(R) \propto$

$R^{-3.5}$, where R is the Galactocentric radius (see e.g. Wetterer and McGraw 1996). If the dark halo were made entirely of dim white dwarfs, they would require a density distribution which follows $\rho(R) \propto R^{-2}$, in order to generate a gravitational field which would account for the observed flat rotation curves of disk galaxies. However, we know from the microlensing results that they do not dominate the total mass of the halo. In that case, they could still have an $R^{-3.5}$ distrubution (as discussed by Gates and Gyuk 2001). In their model, "normal" Cold Dark Matter makes up the rest of the mass distribution and does follow an R^{-2} distribution. For the purposes of the modelling here, the local volume surveyed is so small that the density of the white dwarfs over the volume is essentially constant.

The kinematic properties of all the model populations are shown in Table 4.

3 MODELLING THE LHS AND OHDHS SURVEYS

The model allows us to run Monte-Carlo simulations of a proper motion survey. Stars are generated within a small sphere around the Sun, with a uniform density distribution in the case of the halo and thick disk populations, and with a density distribution which is falling off in z as $\mathrm{sech}^2(z/z_h)$ in the case of the disk (where we adopt $z_h = 125$ pc, which is equivalent to an exponentially falling disk scale height of 250 pc far from the plane).

For each star a V-band absolute magnitude is selected from the appropriate luminosity function, and its apparent magnitude computed. A $V - I$ colour is assigned to the stars as follows:

For the disk M dwarfs we use the empirically calibrated relation due to Reid (1991)

$$(V - I)_{MD} = 0.297 \times M_V - 0.858$$

For the white dwarfs, $V - I$ colors are calculated similarly by a relation:

$$(V - I)_{WD} = 0.385 \times M_V - 4.85$$

This relation comes from fitting white dwarfs in the sample of Bergeron et al (2001). We have also derived transformation equations for white dwarfs from $V - I$ to other colours from the same sample:

$$B - V = 1.05 \times (V - I) - 0.13$$

$$R - I = 0.473 \times (V - I) + 0.01$$

Note that a small Gaussian random number with standard deviation $\sigma = 0.05$ is added to the $V - I$ colour to avoid clutter in the figures.

An absolute magnitude M_V versus colour $V - I$ diagram from a typical simulation of the LHS catalog is shown in Figure 2. Main sequence disk stars dominate the sequence on the right side. The left sequence consists of white dwarfs of the disk, the thick disk and the stellar halo.

3.1 Simulation of the OHDHS survey

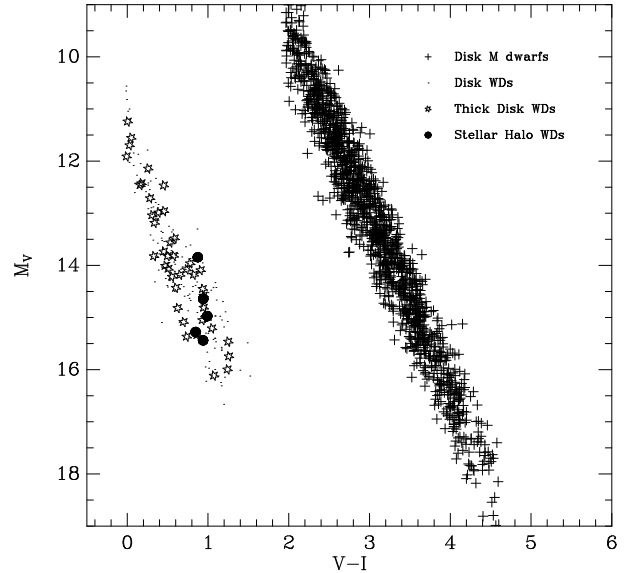The OHDHS survey covers 4165 square degrees, centered on the South Galactic Pole, to a limiting magnitude of

Figure 2. The main components of the model in the M_V versus $V - I$ colour magnitude diagram. A small random number is added after assigning the color to avoid stars settling strictly on a line. The main sequence stars and white dwarfs are clearly separated in this plane.

$R_{59F} = 19.7$ in a proper motion μ window of $0.33 < \mu < 3.0$ arcsecs/year. In order to simulate the OHDHS sample, we generate colour magnitude diagrams of nearby stars using the model described in the previous section. We then transform the M_V and $V - I$ values to the bands used in the OHDHS survey. For *white dwarfs*, we use the following transformations to the (photographic) R_{59F} and the (photographic) B_J bands (i.e. for the III-aJ emulsion) used in the OHDHS survey:

$$R - R_{59F} = \quad 0.006 + 0.059 \times (R - I) - 0.112 \times (R - I)^2$$
$$-0.0238 \times (R - I)^3$$
$$B - B_J = 0.28 \times (B - V) \qquad \text{for } -0.1 \leq B - V \leq 1.6$$

which come from Bessell (1985) and Blair and Gilmore (1982).

For the *M dwarfs* we have derived a transformation from $R - I$ to $B_J - R_{59F}$ based on Figure 10 of Hambly et al (2001), who describe in detail the Super COSMOS sky survey, upon which the OHDHS survey is based.

Figure 3 shows the results of a simulation in the reduced proper motion H_R versus colour $B_J - R$ plane (hereafter, H_R and the R-band refers to the R_{59F} band, used by OHDHS). Panel (a) shows the simulation, and panel (b) shows the actual OHDHS data. Circles mark disk stars, squares mark thick disk stars and triangles stellar halo stars. There is good agreement between the simulated sample and the actual data. Firstly, the disk white dwarfs form a wide sequence from $(B_J - R, H_R) = (0.0, 17.0)$ to $(B_J - R, H_R) = (1.5, 22.0)$. Most white dwarfs appear to be members of the disk. Below this sequence, most of the thick disk and stellar halo white dwarfs appear, because they have generally greater space velocities than the disk stars, and thus higher reduced proper motions.
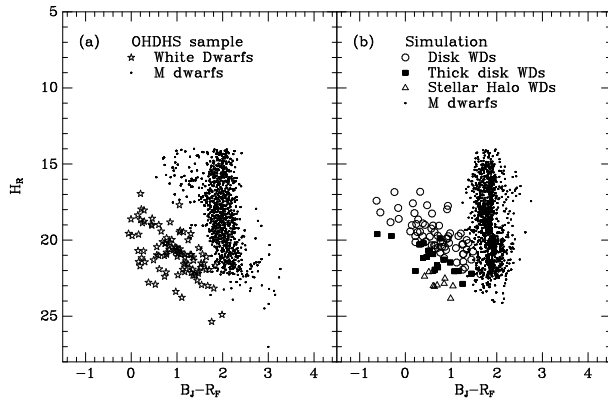
Figure 3. Reduced proper motion versus colour plots for the OHDHS and simulated samples. Panel (a) shows the data from OHDHS, with white dwarfs marked by stars and M dwarfs by dots. Panel (b) shows a typical simulation of the OHDHS survey using our model. The main features of the data are well reproduced by the simulations: most of the white dwarfs detected are plausibly from the disk, thick disk and stellar halo. Two of the OHDHS white dwarfs (at high reduced proper motion) are not easily accounted for by the model, and are very interesting as dark matter candidates.

The M dwarfs lie in an almost vertical line at $B_J - R \approx 2.0$ in both panels. The total number of M dwarfs in the simulation is similar to the observations, as a result of adjusting the kinematic parameters of the disk to acheive this consistency. The number of disk M dwarfs turns out to be quite sensitive to the disk kinematics, and we acheived this good fit by using the kinematic parameters for the disk shown in Table 4. The kinematic parameters adopted are however quite consistent with the observed kinematics of M dwarfs (Upgren et al (1997), and also section 2.1).

To a limiting magnitude of $R = 19.7$, OHDHS identify a total of 97 white dwarfs, of which 82 have direct spectroscopic confirmation, and 15 are assumed with reasonable confidence to be white dwarfs based on their position in the reduced proper motion versus colour diagram.

We have computed the expected numbers of various white dwarf types using the model. The expected numbers are: for the disk 60 ± 8 WDs, for the thick disk 21 ± 5 Wds and for the stellar halo, 10 ± 3 WDs, for a total of 91 WDs.

The adopted kinematical parameters have a small effect on the predicted numbers of white dwarfs. For example, adopting the disk, thick disk and halo kinematics used by Reylé et al (2001), (i.e. for the disk: $\sigma = (42.1, 27.2, 17.2)$ km s^{-1}, and $V_{as} = 16.6$ km s^{-1}, for the thick disk $\sigma = (67, 51, 42)$ km s^{-1}, and $V_{as} = 53$ km s^{-1}, and for the halo $\sigma = (131, 106, 85)$ km s^{-1}, and $V_{as} = 229$ km s^{-1}, compare with Table 4), we obtain 54 disk WDs, 18 thick disk WDs and 11 halo WDs, that is the numbers are very similar.

The total number of white dwarfs in the model and the OHDHS sample are in good agreement. We now check the relative numbers of white dwarfs of each population type. The simulations indicate that a neat dividing line between disk and other types of white dwarfs can be drawn from $(B_J - R, H_R) = (-0.5, 17.0)$ to $(B_J - R, H_R) = (2.0, 26.0)$. Counting white dwarfs below this line in the simulations
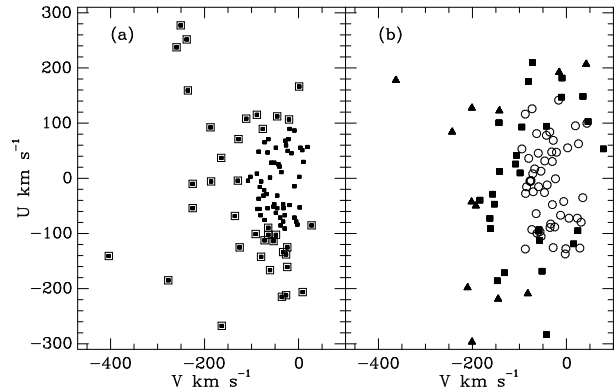

Figure 4. Kinematics of the white dwarfs. Panel (a) shows the V versus the U velocities for the white dwarfs in the Oppenheimer et al sample. Panel (b) shows results from a typical simulation using disk, thick disk and stellar halo white dwarfs, but no dark halo white dwarfs. (The same symbols are used as in Figure 3(b)). The main features of the observations appear to be well reproduced by the classical stellar populations alone.

yields 27 ± 5 stars, compared to 21 white dwarfs in the OHDHS sample.

Oppenheimer et al (2001) argue that many or all of these higher reduced proper motion white dwarfs are part of a new dark halo population, comprising some 2% of the local dark matter halo density. We argue instead that these white dwarfs can just as well be interpreted as coming from a mixture of the thick disk and stellar halo. Further evidence for this assertion comes from the kinematics of the white dwarfs.

We show in Figure 4 the space velocities of the white dwarfs in the V versus U plane, i.e. projected onto the Galactic plane. A typical simulation is shown in panel (a) and the OHDHS sample stars in panel (b). In the simulation, disk stars are marked by diamonds thick disk stars by crosses and halo stars by circles. The similarity between the diagrams is striking. In particular, the thick disk and stellar halo white dwarfs in the simulation lie mostly outside the 2-σ circles used by Oppenheimer et al (2001) to isolate the dark halo stars (squares in squares). (The 2-σ circle is where stars with velocities twice that of the disk velocity dispersion lie, relative to the mean motion of the old disk at $(V, U) = (-35, 0)$ km s^{-1}). In a typical simulation we count 41 ± 6 white dwarfs outside the 2-σ circle, while OHDHS find 37 such stars. The distribution of these simulated stars in the (V, U) plane is also found to be very similar to the observations.

We show in Figure 5 the V versus U velocities for a sample of local dwarf stars for which [Fe/H] is available (Fuchs and Jahreiß, private communication 2001). The availability of abundances means that the stars can be classified by their population type directly, rather than compared statistically to the models (as is the case for the white dwarfs). There are 282 stars in total, of which 245 are in the metallicity range $-1.6 < $ [Fe/H] $ < -0.5$, and are here termed "thick disk" stars, while 37 have [Fe/H] $ < -1.6$ and are here termed "halo" stars. What is striking about this figure is how similarly the (V, U) distribution of the stars is to the OHDHS samlpe (Figure 4(a)). Thick disk stars dominate the region around $(V, U) = (-35, 0)$ km s^{-1}), while the halo stars fill a
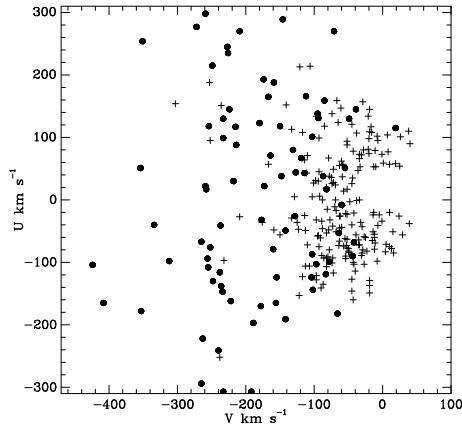
Figure 5. Kinematics of a sample of nearby dwarfs (Fuchs and Jahreiß, private communication 2002). Crosses indicate stars in the range $-1.6 < $ [Fe/H] < -0.5 (broadly, "thick disk" stars) while circles are stars with [Fe/H] < -1.6 (broadly, "halo" stars). The distribution of velocities for the two metallicity types is very similar to that of the white dwarfs of the OHDHS sample (Figure 4(a).

much broader region centered roughly at $(V, U) = (-220, 0)$ $\mathrm{km\,s^{-1}}$).

3.2 Simulation of the LHS

The LHS covers about 28,000 square degrees, mostly of the Northern sky, to a apparent magnitude limit of $R = 18.6$ and with a proper motion window of $0.5 < \mu < 2.5$ arcsec/year. We simulate the LHS by covering the fraction of the sky ($\delta > -33°$ and $|b| > 10°$, i.e. 65% of the sky) which is estimated to be complete to better than 90% by Dawson (1986).

Figure 6 shows the reduced proper motion H_R (RPM) versus colour for the simulated LHS sample, where the Luyten R band magnitude (R_L) is related to the V magnitude via (see Flynn et al 2001, appendix B)

$$R_L = V - 0.17 - 0.228 \times (B - V).$$

Note that we have not shown the M dwarfs in the simulation, because we were unable to obtain satisfactory transformations from $V - I$ to Luyten's photographic $B_L - R_L$ colour.

Although the LHS and the OHDHS surveys probe similar volumes of space, it is much easier to compare our simulations with OHDHS. This is because the OHDHS sources have been spectroscopically classified into white dwarfs and red dwarfs (such work is underway with the LHS and should be available in the near future) and furthermore the colour transformations are better understood than in the LHS. Hence, we regard the comparison of our model with OHDHS in the previous section as superior to any comparison with the LHS. Nevertheless, the broad features of the LHS observations are well reproduced by the simulation, and we regard this as a qualitative consistency check on the model.
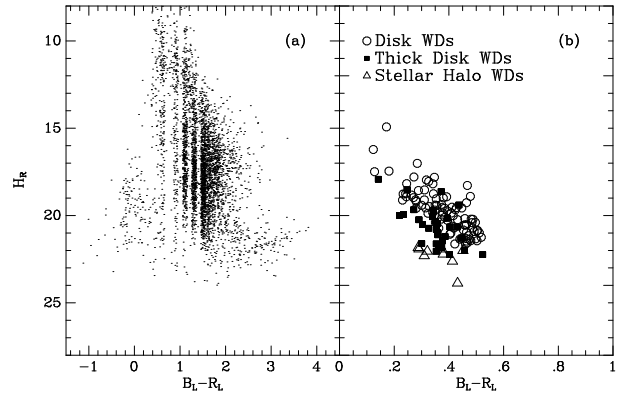

Figure 6. Reduced proper motion versus colour for the LHS sample. Panel (a) shows the data from the LHS, while panel (b) shows a typical simulation (of the white dwarfs only). The white dwarf part of the LHS data is broadly reproduced by the simulation.

3.3 Dark Halo White Dwarfs?

We now introduce dark halo white dwarfs into the simulations. We begin by adopting a luminosity function in which all the dark halo white dwarfs are as faint as the faintest white dwarf found in the OHDHS sample, i.e. at absolute magnitude $M_V = 15.9$. This choice *minimises* the number of dark halo white dwarfs generated in the simulations, while not being inconsistent with the luminosities of the white dwarfs actually found in the OHDHS survey. Still, it appears to produce too may simulated dark halo sources. Following OHDHS, we adopt a white dwarf mass of 0.6 $M_\odot$ and local density of 2% of the dark halo, i.e. $0.02 \times 0.008 = 1.6 \times 10^{-4}$ $M_\odot$ pc^{-3}. In Figure 7 we show where these dark halo white dwarfs lie in the reduced proper motion versus colour plane. Despite being conservative and minimising the number of "dark" white dwarfs, there are plenty of these white dwarfs at a reduced proper motion of $H_R \approx 25$, where just a few stars are found in the observed samples.

Judging from the simulations, a good discriminator between white dwarfs of the disk, thick disk and stellar halo and those of the dark halo is to divide them at $H_R = 24$. In the OHDHS sample, two white dwarfs are found with reduced proper motion $H_R > 24$, while none were found in the LHS. Both samples survey very similar local volumes. We plot in Figure 8 the number of high reduced proper motion white dwarfs ($H_R > 24$) expected in the LHS and OHDHS surveys as a function of their fraction of the dark halo. Assuming that no dark halo white dwarf candidates were found in the LHS, and two (the two absolutely faintest stars) were found in Oppenheimer et al's survey, we conclude that approximately 0.4% of the dark matter density could be in white dwarfs (i.e. 2 WDs were found corresponding to a dark matter fraction of $\approx 0.1\%$ in figure 8). A dark matter fraction of 2%, as suggested by OHDHS, would yield about 12 high reduced proper motion white dwarfs in the OHDHS sample and about 5 in the LHS sample, for a total of 17, compared to 2 WDs actually found. Judging from both surveys, we conclude that OHDHS's estimated fraction of 2% of the dark halo density in white dwarfs is an overestimate, and should be approximately an order of magnitude smaller. If a significant fraction ($> 0.1\%$) of the dark halo is in white
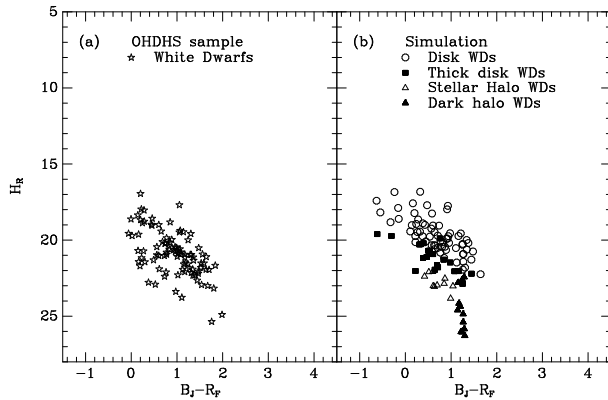
Figure 7. Reduced proper motion versus colour plots for the OHDHS and simulated samples. Panel (a) shows the data from OHDHS, with white dwarfs marked by stars. Panel (b) shows a typical simulation of the OHDHS survey using our model, now including white dwarfs from the dark halo (the figure is otherwise the same as Figure 3). Two percent of the dark halo mass has been placed in white dwarfs of 0.6 $M_\odot$ at an absolute magnitude of $M_V = 15.9$, and these are shown in the simulated survey by filled triangles. Most of the white dwarfs in OHDHS are plausibly from the disk, thick disk and stellar halo, but two high reduced proper motion white dwarfs in OHDHS do lie in the region where dark halo white dwarfs with an absolute magnitude of $M_V = 15.9$ are expected to lie, although (as shown in Figure 8) the simulations produce approximately a factor of ten more such stars than actually seen in the combined LHS and OHDHS surveys.
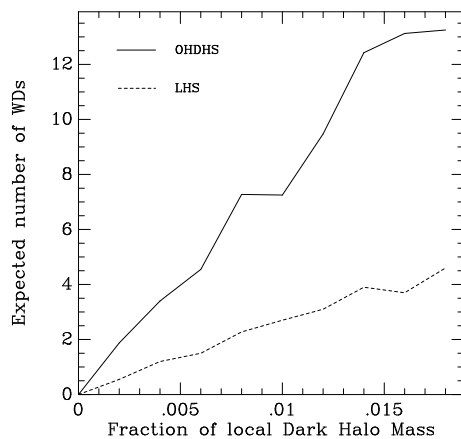

Figure 8. Expected number of high reduced proper motion ($H_R > 24$) white dwarfs in the two surveys analysed, as a function of the fraction of the local dark matter density in such objects (for a white dwarf mass of $M_{WD} = 0.6 M_\odot$. The actual number of objects found in both surveys with this high a reduced proper motion is 2, which corresponds to a local density of $\approx 0.2\%$ of the dark halo. The dark halo density adopted is 0.008 $M_\odot$ pc^{-3}

dwarfs, then they should be fainter than absolute magnitude $M_V \approx 16$ in order to avoid being detected in large numbers in either the LHS or OHDHS.

4 CONCLUSIONS

We have built a model of the kinematics and luminsities of low mass stars in the Solar neighbourhood, which we use to simulate the results of various proper motion surveys. We discuss in particular the search for very faint white dwarfs in the Luyten Half Second proper motion survey and recently by Oppenheimer et al (2001), which are the largest surveys of the type. The surveys sample similar volumes of space. We argue that the contribution of "normal" white dwarfs of the thick disk and stellar halo is sufficient to explain the high velocity white dwarfs found by OHDHS, and that they are not necessarily part of a new, massive population from the dark halo. This work confirms results from a similar study by Reylé et al (2001).

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